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CONTACT THERMAL RESISTANCE

By

Konomo Sonokama

Translated from
Journal of the Japan Society of Mechanical Engineers,
64, No. 505, 240 - 250 (1961)

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CONTACT THERMAL RESISTANCE*

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1. Introduction

When heat flows through the interface of two solids in contact with each other, the surface temperature at random points within the contact area may not necessarily be the same. This is nothing new, and even one who has had no experience in this field can quickly grasp the significance. This apparent discontinuity in contact temperature is due to the existence of a thermal resistance at the surfaces, and this phenomenon has been named contact thermal resistance.**

We do not consider fused junctions here but only mechanical contact. This problem is an important one from the standpoint of thermal transmission in machinery and construction. Otto[1] in 1906 first studied this problem with the

* Received 5 October 1960.
** Recently studies of heat transfer between molten media such as Nak and metal surfaces have become important, and the resistance between the two phases is also called contact thermal resistance. This paper, however, is limited to the resistance between two solid contacting metal surfaces.

use of electrical measuring instruments. In the thirty years which followed, very little work along this line was seen. Only recently with the advent of atomic reactors in which large thermal fluxes have to be considered has this problem been attacked with full vigor.

While there seems to be many areas where contact thermal resistance can not be ignored, detailed descriptions are not available. Whatever treatment that might be available is meager at best. Therefore, it does not seem too meaningless to introduce the problems associated with contact thermal resistance and point out the salient features that need to be considered.

2. Definition and Description of Contact Thermal Resistance

When heat flows through the contact surface between two solids, the thermal resistance encountered at the contact surface is defined as contact thermal resistance. As a result of this resistance, there is an apparent discontinuity in temperature distribution at the contact surface. This transmission phenomenon is called contact thermal conduction. The contact surface in question here is the overall contact area and not a microscopic area. Should infinitesimal areas be considered, surely there would be no temperature discontinuity. This term is often referred to as simply contact resistance, thermal contact resistance, contact surface resistance, or contact surface thermal resistance, and there is considerable confusion. In this paper we will use the term contact thermal resistance. For units the reciprocal, conductance, is often used in place of resistance as is the custom in other countries. The term contact thermal conductance may not seem suitable in view of hithertofore accepted definition of thermal conduction, however, if one considers contact thermal conductance to be a single term to be used for convenience, very little ambiguity should ensue.

Take the situation illustrated in Fig. 1. Two solids, 1 and 2, with respective thermal conducting coefficients λ_1 and λ_2 are in contact with each other through a contact surface A, and Q units of heat per unit time is flowing. Take the respective temperatures to be T_1 and T_2. Assume an x axis to run normal to the contact surface. If one assumes no contact thermal resistance, $T_1 = T_2$, however, in practical cases there is a temperature differential $\Delta T = T_2 - T_1$ as shown

in Fig. 1. Representing contact thermal resistance per unit area by r_c and contact thermal conductance by h_c, the following relations can be set up.

$$Q = \lambda_1 \cdot A \cdot \frac{dT_1}{dx} = \lambda_2 \cdot A \cdot \frac{dT_2}{dx} \quad \cdots\cdots\cdots (1)$$

$$Q = h_c \cdot A \cdot \Delta T = \frac{A}{r_c} \cdot \Delta T \quad \cdots\cdots\cdots (2)$$

$$\therefore \quad r_c = \frac{1}{h_c} = \frac{\Delta T}{\left(\frac{Q}{A}\right)} \quad \cdots\cdots\cdots (3)$$

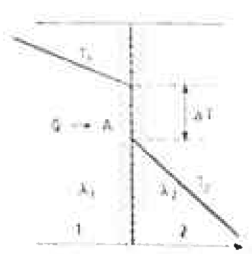


Figure 1.

This can also be illustrated by the method of equivalent lengths. If the temperature difference at the contact surface is Δ T, we divide this value by the slope of the temperature gradient in the solid dT/dx. As shown in Fig. 2, this is the same effect as placing a solid of this length in place of the contact surface. Representing this equivalent

length by l,

$$l = \frac{\Delta T}{\left(\frac{dT}{dx}\right)} \quad \text{.........................} \quad (4)$$

This phenomenon is very easy to see if the two contacting solids are made of the same material. When the two solids are of differ nt materials, this would most likely correspond to contact thermal resistance or conductance. The relation between equivalent length and unit contact thermal resistance or conductance is

$$l = \frac{\lambda}{h_c} = \lambda \cdot r_c \quad \text{———————} \quad (5)$$

Hereafter, contact thermal resistance or conductance will be referred to on the unit basis, and no separate units will be expressed.

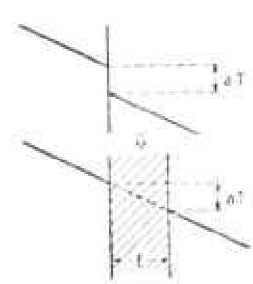


Figure 2.

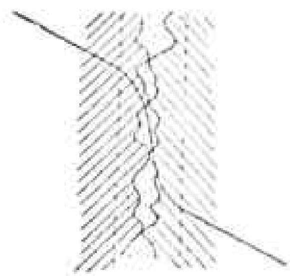


Figure 3.

Next, consider how contact thermal resistance comes about. There are apparent temperature discontinuities at the interface. Looking at a microscopic interface profile in a continuous manner as shown in Fig. 3, very large temperature fluctuations can be seen within the confines of a narrow band. While the surfaces seem to be in good contact when seen microscopically, there are ups and downs on both surfaces such that there are very few points of actual contact. It is usually the case that some material with very low thermal conductivity like air or oil is trapped here such that the overall thermal conductivity is very poor. As a result, the temperature drop per unit thickness is much greater than within either of the solids. Heat flows either through the contact areas or by transmission and radiation through the material filling the void space, and convection effects can be neglected unless there is an exceptionally large void.

What is the relative magnitude of conductance and radiation effects? Assume two solids with temperature T_1 and T_2 separated by distance δ . Further assume air in the void. Letting that quantity of heat conducted to be Q_c and that radiated to be Q_r, the following ratio can be set up.

$$\frac{Q_r}{Q_c} = \frac{\sigma \varepsilon_{12}(T_1^4 - T_2^4)}{\lambda_f \frac{T_1 - T_2}{\delta}} \qquad (6)$$

λ_f is the thermal conductivity coefficient for air, σ is the Stefan-Boltzman constant and ε_{12} is related to the radiation coefficient ε by

$$\varepsilon_{12} = \frac{1}{\frac{2}{\varepsilon} - 1} \qquad (7)$$

Taking mean temperature to be T_0, temperature differential to be ΔT and assuming $\Delta T \ll T_0$

$$T_1^4 - T_2^4 = 4T_0^3 \Delta T \qquad (8)$$

Substituting values of $\varepsilon = 0.7$ and $\delta = 0.01$ mm gives

$$\frac{Q_r}{Q_c} = \frac{4\sigma\varepsilon_{12} T_0^3}{\frac{\lambda_f}{\delta}} = 1.05 \times 10^{-12} \frac{T_0^3}{\lambda_f} \qquad (9)$$

Results calculated from this are shown in Table 1.

This is true only when $\Delta T \ll T_0$. When $\Delta T > T_0$, the fraction radiated increases, and becomes greater the wider the gap. The limiting condition is when there is no actual contact, however, in actual cases there is always some contribution from the contact areas. Outside of some exceptional cases, the radiation contribution from the contact areas is about 2-3 percent of the total, and it can be said that transmission through the interface is mainly by conduction.

We next consider what factors affect contact thermal resistance. The following basic items can be mentioned.

1. Flatness of the contact areas
2. Nature of materials in contact (hardness and thermal conductivity coefficient)
3. Contact pressure
4. Roughness of contact surfaces

5. Material in voids (thermal conductivity coefficient, pressure in case of gasee)
6. State of oxidation of contact surfaces.

Flatness of contact surfaces is very important. There is considerably more contact resistance with microscopic ups and downs at the interface than with microscopic unless the void material is highly conducting. We consider here only surface roughness outside of wavinese and aseume a fairly uniform contact. It must be remembered that wavinese can be a major problem in actual cases.

Table 1.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

3. Theoretical Treatment of Contact Thermal Resistance

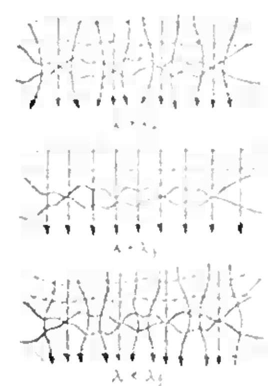
Contact thermal resistance is affected by myriads of subtle factors at the interface, and theoretical treatment is very difficult. It is almost impossible to incorporate all the factors previously mentioned in this treatment, and any such attempt only makes the development more difficult. Therefore, we will omit items whose effects are relatively minor such as the state of oxidation of the contact area and assume homogenous materials. It is needless to mention that a theoretical treatment of any surface must entail detailed knowledge of the surface itself. Statistical analysis of surface roughness or study of contact mechanisms are necessary, and studies along these lines are quite prevalent.

There are many treatments developed from the standpoint of contact electrical resistance, friction, lubricating or elastic plasticity, however, there is still need to combine the effects of thermal resistance at the interface to bring about a more rigorous treatment of contact phenomena,

Should the thermal conductivity coefficient of the void material λ_f be the same as that of the solid material itself, thermal flow lines are normal to the line of contact, and isothermals parallel to the seam will result. When these coefficiente differ, isothermals with uneven fronts would be

thought to result as shown in Fig. 4. This unevenness should persist for only a short distance from line of contact, and the net effect of this remains in doubt. If the net effect is small, there would be little need to consider surface roughness in this treatment.

At the present, there are at most two or three theoretical treatments and they will be considered below.



Thermal flow lines
Isothermal

Figure 4.

3.1 Hashi's Work[10,13]

Professor Hashi of the Technical Production Laboratory, Tokyo University has been working on the problem of contact thermal resistance since 1944. He has tentatively arrived at a result that isothermals parallel to the seam result and has come forth with qualitative and quantitative explanations.

If one accepts this theory, flow of heat through a junction will be independent of surface conditions, and only contact area and void area need to be considered.

Take surface irregularity to be expressed by $y = f(x)$ and select a fairly broad interval $(b - a)$. Take maximum peak height to be h_{max} and mean height to be h_m, the following relation can be set up.

$$\delta = \frac{\int_a^b (h_{max} - y)dx}{b - a} = h_{max} - h_m \qquad (10)$$

The direct contact area a is related to apparent contact area A, Brinnell hardness H_B and contact pressure P by the following relation.

$$P \cdot \frac{A}{a} = c \cdot H_B \qquad (11)$$

c is a constant that needs to be determined.

Now consider columns of length as shown in Fig. 6, with total contact area a to represent the picture at the interface. This greatly simplifies calculating contact thermal resistance, however, Hashi introduced the equivalent length on the basis that this represents contact thermal resistance at the metal-metal interface.

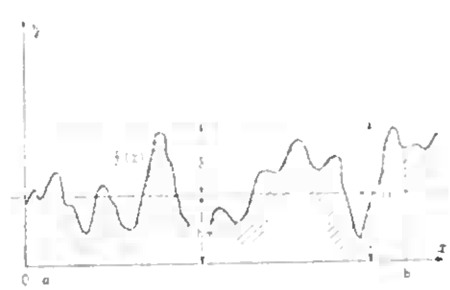
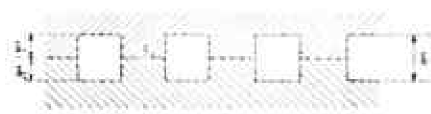


Figure 5.

$$\frac{1}{l} = \left[\frac{1}{\delta \cdot \delta_0} - \frac{1}{\delta} \cdot \frac{\lambda_f}{\lambda} \right] \frac{P}{c \cdot H_B} + \frac{1}{\delta} \cdot \frac{\lambda_f}{\lambda} \qquad (12)$$

and c are unknown constants. c is a value investigated in other areas such as elastic plasticity theory and is usually taken to be about unity. Hashi's results also indicate this to be the case. is a value which can be obtained only from contact thermal resistance measurements, and Hashi's data indicate it to range from one to ten times that of .



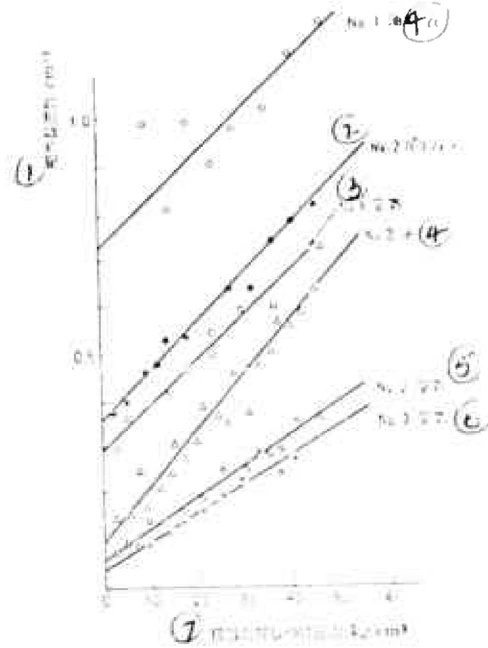
is equivalent length of direct contact section

Figure 6.

When the thermal conductivity coefficient of void material in (12) is smaller than that of metal, the following approximation is made.

$$\frac{1}{l} \approx \frac{1}{\delta \cdot \delta_0} \cdot \frac{P}{c \cdot H_B} + \frac{1}{\delta} \cdot \frac{\lambda_f}{\lambda} \qquad (13)$$

This conveniently relates contact pressure directly with reciprocal of equivalent length. This relation holds in the region where contact pressure is not excessive, and the data of Fig. 7 bear this out.



Maximum height of contacting metal:
No. 1 6 μ, No. 2 22 μ, No. 3 37 μ
Air, oil or paraffin as void material

Figure 7. (from Hashi)

Legend:
1. Reciprocal equivalent length cm^{-1}
2. No. 2 paraffin
3. No. 1 air
4. No. 2 oil 4a No. 1 oil
5. No. 2 air
6. No. 2 air
7. Contact pressure kg/cm^2

The following can be concluded from Hashi's results.

1. Under the same general conditions, softer materials show smaller contact thermal resistance.
2. Finishing the surface and increasing contact pressure lower contact thermal resistance. Within the limits of moderate contact pressure, void volume can be considered to be constant. Finishing contact surface decreases resistance not by increasing contact surface but by decreasing mean height of ridges.
3. Effect of surface conditions can be considered only in the light of mean ridge height.
4. With metal normally used and within the confines of moderate contact pressures, the direct contact area is a small fraction of the apparent contact area. As a result, contact thermal resistance will be nearly completely a function of the thermal conductivity coefficient of void material and void spacing.

3.2 Studies of Centikale and Fischenden[12]

Centidale and Fischenden assumed that isothermals were not parallel to the seam and made their calculations on the basis that thermal flow gave rise to contracted flow patterns. It is needless to say that one needs to know surface unevenness to arrive at thermal front unevenness, however, it is rather impractical to apply surface unevenness directly. They represented this unevenness by columnar projections which were assumed to be uniformly distributed. Assuming projections of equal height and spaced uniformly apart, only one projection as shown in Fig. 8 needs to be considered.

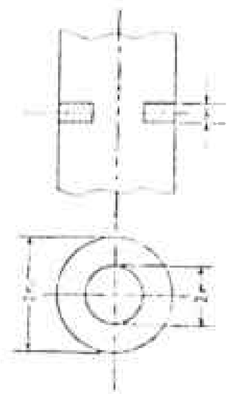


Figure 8.

If the confocal thermal flow lines shown by the dotted line and isothermals of Fig. 9 are assumed to give confocal surfaces, thermal resistance calculations are simplified. Taking the thermal resistance of solid to be R_s

$$R_s = \frac{1}{2\pi r \lambda_1} \tan^{-1} \frac{r_e - r}{r} \quad \cdots\cdots\cdots \quad (14)$$

The resistance of void material assuming void coefficient be f is

$$R_f = \frac{\delta_1}{\pi r_e^2 \lambda_f} \quad \cdots\cdots \quad (15)$$

The desired resistance R_c can be thought to be a parallel hookup of the two.

$$\frac{1}{R_c} = \frac{1}{R_s} + \frac{1}{R_f} = \frac{\pi r_e^2 \lambda_f}{\delta_1} + \frac{2\pi r \lambda_1}{\tan^{-1} \frac{r_1 - r}{r}} \quad (16)$$

Thus far only one of the contacting solids has been considered. Take the respective thermal conductivity coefficients of the two contacting solids to be λ_1 and λ_2 and column projections δ_1 and δ_2. Substituting the following

$$\delta = \delta_1 + \delta_2 \tag{17}$$

$$\frac{1}{\lambda} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} \tag{18}$$

into (16) gives

$$\frac{1}{R_c} = \frac{\pi r_e^2 \lambda_f}{\delta} + \frac{\pi r \lambda}{\tan^{-1} \frac{r_e}{r}} \tag{19}$$

Next, convert to nondimensional terms.

$$U = 1 + \frac{BC}{K \tan^{-1}\left\{ \frac{1}{C} \sqrt{1 - \frac{1}{U}} - 1 \right\}} \tag{20}$$

Conductance number $U = \frac{\delta}{R_c \pi r_e^2 \lambda_f}$

Constriction number $C = \frac{r}{r_e}$

Conductivity number $K = \frac{\lambda_f}{\lambda}$

Fluid thickness number $B = \frac{\delta}{r_e}$

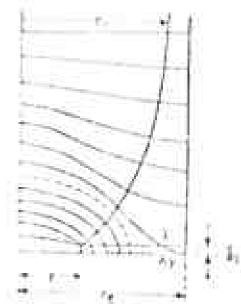


Figure 9.

The nondimensional numbers K, C, and B can be established once the contact and void materials and contact surface state are known. The problem is how to convert surface roughness into equivalent columnar projections.

Taking Meyer hardness to be H_M, C can be given by

$$C = \sqrt{\frac{P}{H_M}} \qquad (21)$$

If pressure is increased to P_{max} and then relaxed to P,

$$C = \sqrt{\frac{P^{1/3} P_{max}^{2/3}}{H_M}} \qquad (22)$$

Next, to obtain B the columnar projection height, and radius r_e of a single column need to be known. We take the arithmetic mean interval of the geometric surface irregularities to be ℓ_c and the respective wavelengths of surface roughness to be λ_1 and λ_2 and assume the following.

$$\beta = \varepsilon \beta_c \qquad (23)$$

$$r_c = \psi \cdot (\lambda_1 / \lambda_2) \cdot C^{\xi} \qquad (24)$$

[illegible] , [illegible] , and [illegible] are constants which do not depend on the nature of the solid and void material. Centikale and Fishchenden obtained values of [illegible] = 0.61, [illegible] = 0.0048, and [illegible] = -5/3 from experiment.

3.3 Studies of Fenech and Rohsenow[29]

This treatment also utilizes columnar projections to represent surface irregularities. It differs from the previous treatment in that temperature distributions in the columns are calculated directly from heat conduction equations.

As shown in Fig. 10, each solid is divided into four regions, I, I, III, and IV. This is the so-called composite process in which the thermal conductivity equation for each region is solved and the results are combined taking into account boundary conditions. Fenech's group varied the eigenvalues which are the solutions to the first and second types of Bessel functions and expressed them as functions of r. The following solution was assumed.

$$T = T_0 + g(z+d) + BJ_0(\beta r)e^{-\beta z} + CY_0(\gamma r)e^{-\gamma z} \qquad (25)$$

T_0, g, d, B, C, [illegible] , and [illegible] are constants. One example of boundary conditions is

$$\int_0^{c} (T_{I} - T_{II}) \cdot r \cdot dr = 0$$

$$\int_0 \frac{\partial}{\partial z} (T_{I} - T_{II}) \cdot r \, dr = 0$$

These integrals are not rigorous. The following relation for contact thermal conductance is obtained.

$$h_c = \frac{\frac{\lambda_f}{\delta_1+\delta_2}\left[(1-\varepsilon^2)\left(\frac{4.26\sqrt{n}\frac{\delta_1}{\varepsilon}+1}{\lambda_1}+\frac{4.26\sqrt{n}\frac{\delta_2}{\varepsilon}+1}{\lambda_2}\right)+1.1\varepsilon f(\varepsilon)\left(\frac{1}{\lambda_1}+\frac{1}{\lambda_2}\right)\right]+4.26\varepsilon\sqrt{n}}{(1-\varepsilon^2)\left[1-\frac{\lambda_f}{\delta_1+\delta_2}\left(\frac{\delta_1}{\lambda_1}+\frac{\delta_2}{\lambda_2}\right)\right]\left[\frac{4.26\sqrt{n}\frac{\delta_1}{\varepsilon}+1}{\lambda_1}+\frac{4.26\sqrt{n}\frac{\delta_2}{\varepsilon}+1}{\lambda_2}\right]} \qquad (26)$$

n is a number associated with unit area of columnar projection, ε is r_1/r_2, λ and are respective thermal conductivity coefficients, the subscripts 1 and 2 appended to column heights indicate respective solids, and f refers to the void material. $f(\varepsilon)$ is given by the following function.

$$f(\varepsilon) = \frac{Y_1(2.20\,\varepsilon)\cdot J_1(3.83\,\varepsilon) - J_0(3.83\,\varepsilon)\cdot Y_1(2.20\,\varepsilon)}{1.75\,Y_0(2.20\,\varepsilon)\cdot J_1(3.83\,\varepsilon) - J_0(3.83\,\varepsilon)\cdot Y_1(2.20\,\varepsilon)} \qquad (27)$$

As shown in Fig. 11, this function can be taken to be 1.1 as long as 0.1.

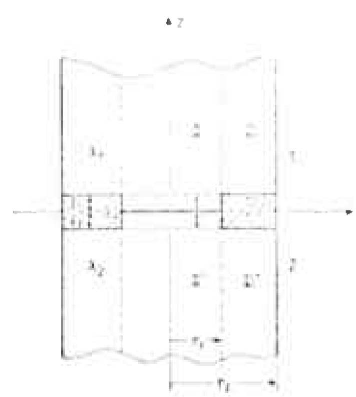


Figure 10.

n, ξ, and a are determined in the following manner. As shown in Fig. 12, x and y axes are projected, and an area l_x by l_y is selected. The number of contact points along l_x and l_y are counted. If these are taken to be n_x and n_y, the number of contact points per unit area is

$$n = \frac{n_x \cdot n_y}{l_x \cdot l_y} \qquad (28)$$

To get at ξ, the void area A_x and A_y using the same axes are obtained from the surface roughness curve. These are divided by the distance considered

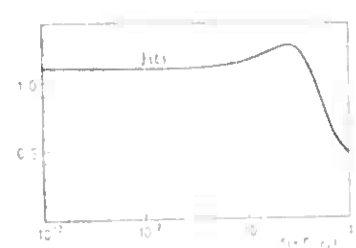
$$\xi_x = \frac{A_x}{l_x}, \quad \xi_y = \frac{A_y}{l_y} \qquad (29)$$

Now take the surface roughness curve in the y direction and obtain lengths y_1 where the line $2/3\,\xi_x$ intersects the roughness curve. From this result we get

$$a = \frac{\Sigma y_1}{l_x} \qquad (30)$$

From this value is calculated the mean height ξ.

$$\xi = \xi_x + \xi_y(1-a) \qquad (31)$$



(from Fenech and Rohsenow)

Figure 11.

The value of δ is obtained from

$$\delta = \frac{\xi}{1 - \frac{\lambda_r}{\lambda}} \qquad (32)$$

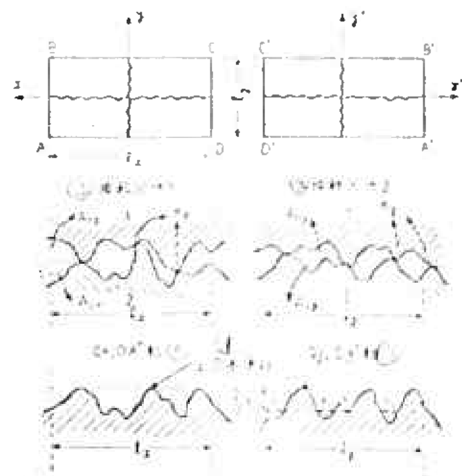


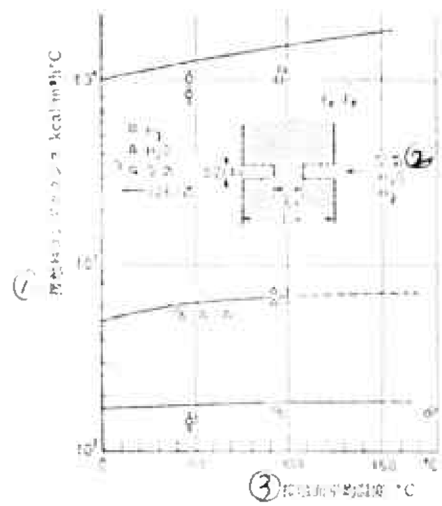
Figure 12.

1. Upper base line 2. Solid 3. Axis

Taking solid hardness to be H and contact pressure to be P, ξ can be expressed by $P = \xi^2 H$. On the other hand, Bishop, Hill, and Mott assumed plastic deformation and found that contact pressure was about three times elastic limit Y. Assuming contact pressure to be of the same order as H, they used the relation

$$H = 3Y \qquad (33)$$

The Fenech group took a centrally constricted columnar piece like that illustrated in Fig. 13 and carried out tests from which they found good agreement with calculated values. It must be said that it is very difficult to carry out a projection of this type.



(from Fenech and Rohsenow)

Figure 13

Legend: 1. Contact thermal conductance
2. Air
3. Contact surface temperature

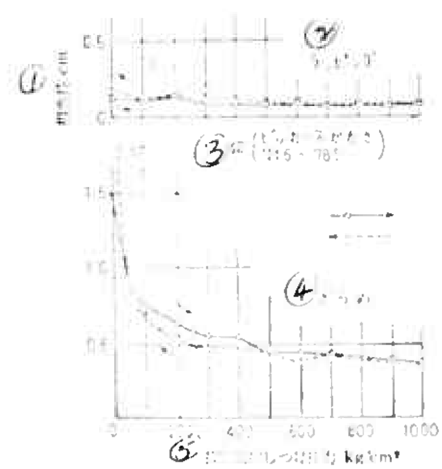
4. Experiments on Contact Thermal Resistance and Future Problems

In this section, representative experimental work will be discussed with the view to bring out the nature of this phenomenon as well as to indicate what problems still exist for future study.

4.1 Effect of Contact Pressure

It has long been known that contact thermal resistance is considerably affected by contact pressure.

Figure 14 shows results from applying and releasing a pressure of 1000 kg/cm^2 to steel. This effect has been observed by all investigators in this field. There is still doubt as to whether the material returns to the original state after the load is removed. Figures 15 and 16 show that when pressures are applied and relieved in small increments over a moderate range, there is not a return to the original state. The magnitude of this change is tied in with the hardness With a material as soft as lead is tested, there seems to be no change in contact resistance from the value at maximum load. In any event, the surface has undergone plastic deformation, and the net result of this deformation can be as large as that observed with lead.



(from Nishiwaki and Ogi)

Figure 14

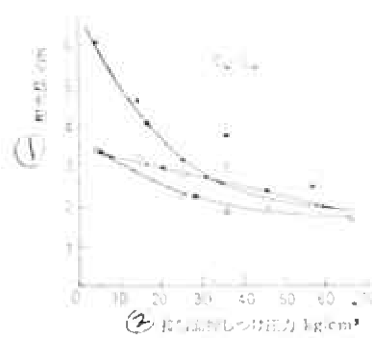
Legend: 1. Equivalent length 2. Lapping
3. Steel (Bicker's hardness 746-785)
4. Filing
5. Contact pressure kg/cm^2

4.2 Effect of Surface Roughness

Surface roughness has considerable effect on contact thermal resistance as shown by the difference in results shown in Fig. 14. Here surfaces finished by lapping and filing are compared. While the smoothness indices of Fig. 17 are not accurate, the trend of decreasing contact thermal resistance with decreasing roughness is clearly shown. Attention must be placed on surface roughness together with surface planarity. If only surface roughness is considered, there may be times when a rougher surface may have less contact thermal resistance than a smoother surface. This is shown in Fig. 18.

4.3 Effect of Hardness

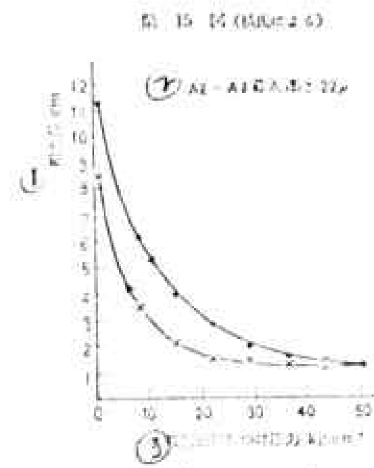
At the same contact pressure and with materials of the same finish, softer materials show smaller contact thermal resistance. This was found from testing several materials and the results are shown in Figs. 19-21.



(from Hashi)

Figure 15

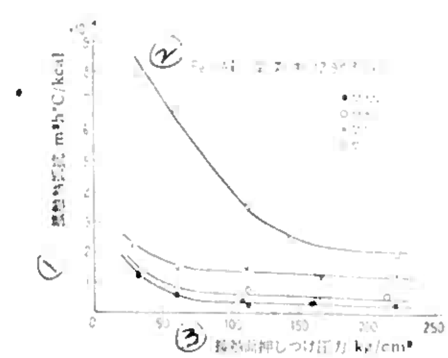
Legend: 1. Equivalent length cm
2. Contact pressure kg/cm^2



(author)

Figure 16

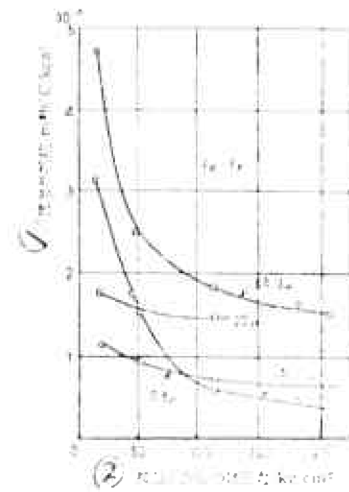
Legend: 1. Equivalent length cm
2. Maximum height
3. Contact preseure kg/cm^2



(from Ascoli and Germagnoli)

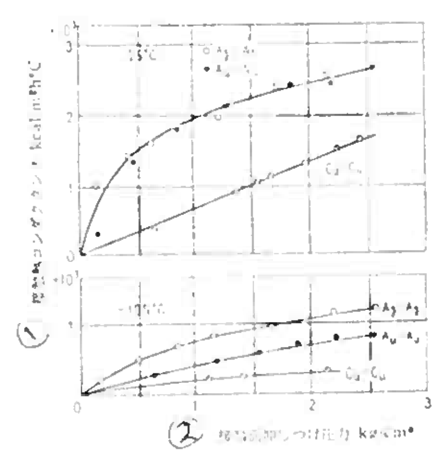
Figure 17

Legend: 1. Contact thermal resistance 2. in air 3. Contact pressure kg/cm^2



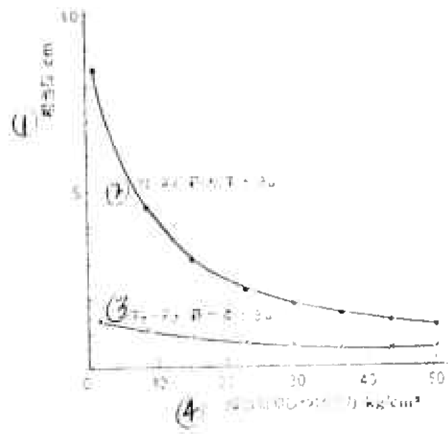
(from Kouwenhoven and Potter)
Figure 18

Legend: 1. Contact thermal resistance
2. Contact pressure kg/cm^2



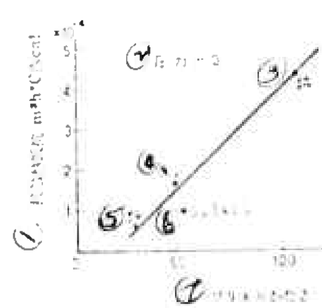
(from Jacobs and Starr)
Figure 19

Legend: 1. Contact thermal conductance
2. Contact pressure kg/cm^2



(author)
Figure 20

Legend: 1. Equivalent length cm
2. Maximum height
3. Maximum height
4. Contact pressure kg/cm^2

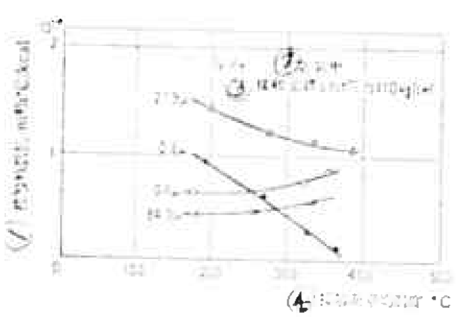


(from Hashi)
Figure 21

Legend: 1. Contact thermal resistance 2. Fixed pressure
3. Steel 4. Brass 5. Copper 6. Duralumin
7. Brinnell hardness

4.4 Effect of the Mean Temperature of Contacting Surfaces

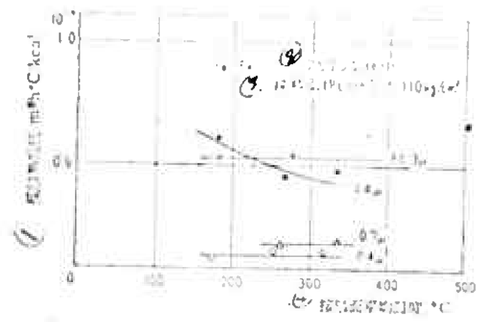
The change in thermal conductivity of void material or corresponding change in solid hardness with mean temperature is not an intrinsic property. The results of Figs. 22 and 23 show that up to 500°C there are no unusually great changes, but trends which are contrary to the expected are difficult to explain. On the other hand, void material is most frequently air whose thermal conductivity increases with temperature such that contact thermal resistance decreases. This situation is clearly shown in Fig. 24. Should the conductivity of void material change in the reverse manner, resistance should then increase.



(from Kouwenhoven and Potter)

Figure 22

Legend: 1. Contact thermal resistance
2. In air
3. Contact pressure
4. Mean Contact surface temperature °C



(from Kouwenhoven and Potter)

Figure 23

Legend 1. Contact thermal resistance
2. In Argon
3. Contact pressure kg/cm^2
4. Mean contact surface temperature ^{o}C

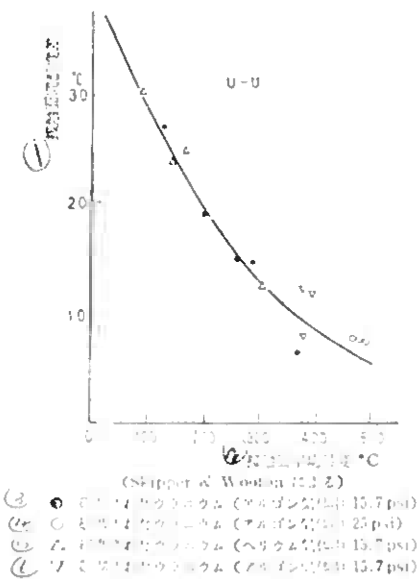
4.5 Effect of Void Material

Comparing results of Fig. 17 in which void material was air with results from Fig. 25 with nitrogen as void material shows small differences in behavior despite the nearly equal behavior of their thermal conductivity coefficients with temperature. Generally speaking, the better the thermal conductivity coefficient of material filling the void, the lower contact thermal resistance. This can be seen from Figs. 7 and 26.

4.6 Effect of the Pressure of Gas in Void

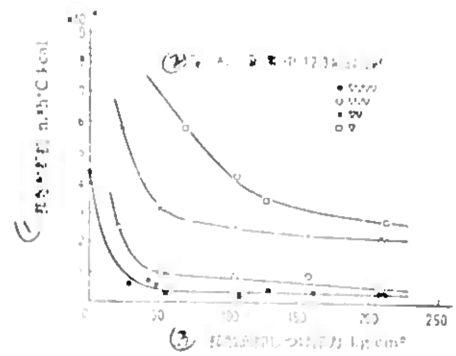
When void material is gas, changes in pressure alter gas density resulting in changes in thermal conductivity coefficient. This effect has been studied and some results are shown in Figs. 26 and 27. When helium is the void gas, de-

creasing pressure increases contact thermal resistance which is as expected. The change, however, comes in the pressure range of 10-100 mmHg and very little change is seen beyond these limits.



Legend: 1. Temperature differences between contacting surfaces
2. Mean contact surface temperature °C
(from Skipper and Wooton)
3. polished uranium (in argon 15.7 psi)
4. polished uranium (in argon 25 psi)
5. polished uranium (in helium 15.7 psi)
6. polished uranium (in argon 15.7 psi)

Figure 24



(from Ascoli and Germanoli)

Figure 25

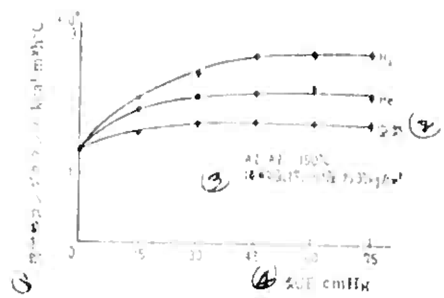
Legend: 1. Contact thermal resistance
2. in air 12.9 kcal/cm^2
3. Contact pressure kg/cm^2

4.7 Effect of Surface Oxidation

The degree of oxidation of the surface has considerable effect on contact thermal resistance, and experimental results are shown in Fig. 28. If oxidation actually has this large effect on contact thermal resistance, it should be a fairly critical problem.

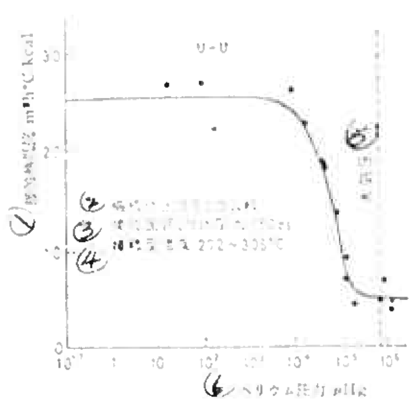
Besides the items mentioned above, it can be added that placing a soft metal foil between the two solids considerably reduces contact thermal resistance. Also, when two differing materials are placed in contact, contact thermal resistance will be mostly determined by the properties of the softer material. It is felt that the essential items, however, have been discussed above.

The above has been a brief survey of the way contact thermal resistance is affected by varying different factors and representative experimental contributions by various workers have been picked to illustrate the points. It is felt that experimental areas are far from being exhausted.



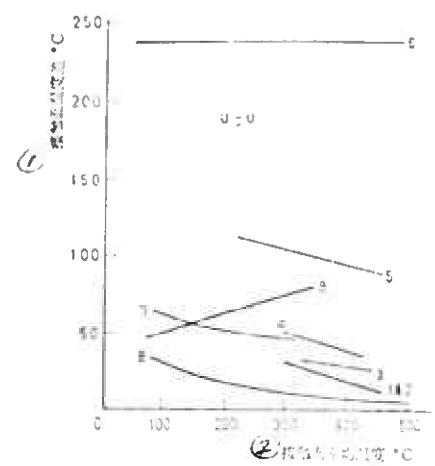
(from Boeschten and Van der Held)
Figure 26

Legend: 1. Contact thermal conductance
2. Air
3. Contact pressure
4. Gas pressure



(from Skipper and Wooton)
Figure 27

Legend: 1. Contact thermal resistance
2. Mechanically finished uranium plate
3. Contact pressure
4. Contact temperature
5. Atmospheric pressure
6. Helium pressure



1. Unoxidized test piece (in argon 18.4 psi)
2. Unoxidized test piece (in argon 17.0 psi)
3. Oxidized test piece (oxide film 0.0004 in., in argon 16.1 psi)
4. Oxidized test piece (oxide film 0.0005 in., in argon 18.4 psi)
5. Oxidized test piece (oxide film 0.0014 in., in argon 16.9 psi)
6. Oxidized test piece (oxide film 0.0021 in., in helium 15.7 psi)
7. Oxidized test piece (oxide film 0.0014 in., in helium 15.3 psi)
8. Unoxidized test piece (in helium 14.7-15.7 psi)
9. Oxidized test piece (in helium 15.7 psi)

(from Shipper and Wooton)

Figure 28

Legend: 1. Temperature difference between contact surface
2. Mean contact surface temperature

Experimental results vary with experimenters, and even results from the same worker often are in contradiction. This may indicate that some important factors have been overlooked or factors are so complexly interconnected that experimental approaches have succeeded in but scratching the surface. In the case of surface roughness, when there are visible irregularities, indices of surface roughness become meaningless.

If surface oxidation is as critical as indications show, it may not be prudent to spend too much time on items such as surface roughness. It is still the case that many of the factors which affect contact thermal resistance are not clearly understood. Accurate and reliable computations are not possible, and there is considerable scatter in results. When such data are used to verify different factors, only the most pertinent items should be pursued since the work is complicated though seemingly simple. It is hoped that future work will clarify these fields.

5. Postscript

Much more was intended in this limited manuscript, however, many details have been deleted. There is a suspicion that many important points have been overlooked. Despite its shortcomings, it is hoped that this paper will be some use to workers in thermal conductivity technology.

Professor Hashi of Tokyo University reviewed this manuscript and offered valuable advice. Mr. Mitsuo Ouchi of this Laboratory prepared the figures in this text. The author gratefully acknowledges their help.

For convenience in making comparisons, the following units were used throughout the figures: temperature in ^{o}C, equivalent length in cm, contact thermal resistance in $M^{2}h^{o}C/kcal$, contact thermal conductance in $kcal/m^{2}h^{o}C$, contact pressure in kg/cm^{2}. The author is responsible for all the calculated values.

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